UCRL- 94817
PREPRINT

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This paper was prepared for submittal to the
Physical Review Letters

June 27, 1986

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November 22, 1985

ABSTRACT

The recently demonstrated technique of laser guiding[1] has been used to successfully propagate a 10 kA relativistic electron beam 95 meters through the Advanced Test Accelerator and post-accelerator beamline. The maximum transverse displacement of the beam at the end of ATA was 1 mm while the maximum beam breakup amplitude was 0.1 mm. The use of laser guiding constitutes a breakthrough in accelerator technology in that it is able to greatly reduce or even suppress the Beam Breakup Instability, which is the most serious obstacle to high current beam transport in linear induction accelerators.

PACS numbers: 41.80.Ee, 07.77. + P, 52.40.Mj

*Work performed jointly under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-ENG-48 and for the Department of Defense under Defense Advanced Research Projects Agency ARPA Order No. 4395, monitored by Naval Surface Weapons Center under document number N60921-86-POW0001; and Naval Surface Weapons Center under document number N60921-86-POW0002.

For many years it has been realized that the major limitation to the transport of high current beams in linear accelerators is the growth of a beam-accelerator cavity instability known as Beam Breakup (BBU).[2,3] A beam which is displaced from the centerline of an accelerating cavity will excite various modes of the structure. The modes which couple most strongly to the beam are the TM_{1n0} modes which give rise to beam breakup. These modes are characterized by axial electric fields which are able to extract energy from the beam and transverse magnetic fields which are non-zero on the axis of the cavity. The instability grows since the Lorentz force exerted on the beam by these transverse magnetic fields is out of phase with the instantaneous displacement of the beam so that the instability cannot be suppressed with linear focusing.

For an accelerator with a constant strength solenoidal field, the amplitude ξ of the BBU, grows with distance down the machine as[2,4]

$$\xi = \xi_0 \exp\left[I_b \omega_0 Z_\perp (mc^2/\Delta E_g)(\gamma - \gamma_i)/(I_0 k_0)\right] . \tag{1}$$

Here I_b is the beam current in kA; $I_0 = mc^3/e \approx 17$ kA; $\omega_0 Z_\perp$ is the product of the angular frequency, the transverse shunt impedance and the quality factor or Q of the relevant cavity mode; $k_0 = eB/mc^2$; γ and γ_i are respectively, the final and initial Lorentz factors of the beam in the solenoidal channel. The factor $mc^2/\Delta E_g$ is the inverse of the change in γ per accelerating gap (ΔE_g is the change in beam energy per gap). ξ_0 is the initial noise level at the resonant frequency of the mode and we have assumed that the energy of the beam grows linearly with axial distance.

In the Advanced Test Accelerator (ATA) focusing is provided by some 250 solenoids spaced closely enough so that the focusing is approximately continuous. The maximum axial field possible in ATA is 3 kG. The accelerator consists of 174 accelerating cavities grouped in various blocks which are separated by short (~ 0.5 m) transport lines (also containing solenoids). There is 1 block of 9 cells, 5 blocks of 5 cells and 14 blocks of 10 cells. Each cavity provides a nominal accelerating voltage of 250 kV. The beam is formed from a velvet cloth field emission cathode inside a 2.5 MeV injector.

The expected amplitude of the BBU at the end of ATA versus peak beam current is shown in Fig. 1. These results are based on Equation (1), and on the measured cavity mode parameters and initial injector noise levels of ATA. It is clear that operation of ATA at its design value of 10 kA with 3 kG solenoidal focusing is not possible. Figure 2 shows the results of an attempt to propagate a 7 kA beam through ATA using solenoidal guiding. BBU grew to such an extent that it caused the tail of the pulse to hit the beam pipe. As a result, only half of the injected charge survived through the accelerator and the large, transverse centroid displacement as a function of time at the accelerator exit rendered the beam totally unusable.

The use of phase-mix damping provided by non-conventional focusing schemes as a possible means to suppress unwanted beam transverse motion has been under study for some time.[5,6] From the perspective of controlling beam instabilities ion channel guiding has three important advantages. First, it is possible to adjust the ion density to make very strong channels resulting in short betatron wavelengths. Second is the favorable scaling of the betatron wavelength with energy. The betatron wavelength of a solenoid channel or an alternating quadrupole channel increases as γ while the betatron wavelength of the ion channel increases only as $\sqrt{\gamma}$ leading to significant increases in focusing strength (as compared to quadrupole channels) with increasing beam energy. The image displacement instability has a similar scaling with energy so that the use of ion guiding can be made to suppress this instability at all energies. Third, the electrostatic potential of the ion channel is anharmonic leading to a spread in the betatron wavelength of the beam electrons.

The spread in the betatron wavenumber due to the non-linear restoring force of the channel has profound implications for the beam breakup instability. Indeed, if the spread in k_β is sufficently great acceleration to arbitrarily high energy is possible without any BBU growth whatever. If ϵ is the fractional spread in k_β^2 it can be shown that the condition for complete suppression of BBU for an accelerated beam is[4]

$$\epsilon k_i^{\,2} > \pi(\omega_o Z_\perp / L_g)(I/I_o) \tag{2}$$

where $k_i^2 = \gamma k_\beta^2 \approx 2e\lambda/(mc^2a^2)$, a is the channel radius, λ is the total channel charge per unit length and L_g is the average spacing between accelerator cavities. For ATA $\omega_o Z_\perp \approx .2\ \mathrm{cm}^{-1}$, $L_g \approx 33$ cm and $k_i^2 \approx .12\ \mathrm{cm}^{-2}$ corresponding to an ion density of $\approx 7 \times 10^{10}\ \mathrm{cm}^{-3}$ and a channel radius of $\approx .75$ cm. Equation (2) predicts that a 5% spread in k_β will stabilize a 10 kA beam.

A practical realization of the phase-mix damping technique was demonstrated by laser guiding a 4.5 MeV, 7 kA electron beam for 4 meters downstream of the Experimental Test Accelerator.[1] Those experiments demonstrated damping of both deliberately induced BBU as well as intrinsic beam sweep. We report here the first use of this technique to guide, focus and provide phase-mix damping of a beam inside an accelerator.

Benzene gas was metered into the accelerator at vacuum pump stations from a header maintained at ≈ 75 Torr vapor pressure by a 200 ml reservoir of liquid benzene. Pressure was measured at each station by an ion gauge and was controlled by a throttling valve at each pump to maintain a uniform pressure profile of 0.1 - 0.2 mTorr from the 6 MeV point throughout ATA to a position 31 meters downstream of the 50 MeV end of the accelerator. The total flow rate into the accelerator ranged from 1 - 6 scc/min so that the benzene volume within the laser channel was replenished at a rate of up to 2 Hz. A commercially available KrF laser was fired through a hole in the cathode in the direction of electron beam propagation. External optics were used to steer and down-collimate the beam prior to introducing it through an uncoated vacuum window at the rear of the accelerator injector. Solenoidal focusing was used in the 2.5 MeV injector and in the accelerator up to the 6 MeV point. The magnetic field was gradually reduced to zero over a distance of approximately 5 meters. The benzene pressure was gradually increased to its full value over the same distance.

The laser pulses had nominally flat rectangular intensity profiles of 12 x 7 or 20 x 13 mm at injection. The spatial profiles were aberrated after propagating 100 m, but total pulse energy was contained within 60 μrad with shot-to-shot centroid jitter < 100 μrad. By decoupling the internal optics of the laser from vibrations of the housing this jitter has recently been reduced to < 10 μrad. The laser pulse preceded the electron beam by 0-150 nsec with both run at 0.2 - 1 Hz repetition rates. Calculations based on solutions to a multilevel rate equation model suggest that the benzene gas was ionized to ≈1%.[7] Figure 3 shows a schematic of the ATA beamline.

The use of laser guiding dramatically improved beam transport on ATA. Figure 4 shows the results for guiding a full 10 kA pulse through ATA. The final BBU amplitude was on the order of 0.1 mm. Transverse displacements at all frequencies totaled less than 1 mm.

It turns out that the strength of the channel guiding is so much stronger than that of the solenoids that it is possible to account for nearly all of the BBU reduction without invoking the effects of phase-mix damping. The growth of the BBU amplitude in an ion channel of constant strength is given by[4]

$$\xi = \xi_o(\gamma_i/\gamma)^{1/4}\exp[I_b\omega_o Z_\perp(mc^2/\Delta E_g)(\sqrt{\gamma} - \sqrt{\gamma_i})/(2I_o k_i)] \quad (3)$$

The different energy dependence in the exponents of Eqs. (1) and (2) results from the different energy dependence of the respective betatron wavenumbers for solenoidal and channel guiding. That is, for the case of solenoidal guiding $k_c = eB/(\gamma mc^2)$ while for ion guiding $k_\beta^2 = 2e\lambda/(\gamma mc^2 a^2)$.

In summary, we have achieved full 10 kA operation of ATA by the use of the laser guiding transport technique. The beam breakup instability, which prevented full current operation of ATA with solenoidal guiding, was reduced by three orders of magnitude to an amplitude of 0.1 mm while transverse offsets of the beam at all frequencies were less than 1 mm. Full beam current was also transported through an additional 31 meters of beamline downstream of the accelerator for a total propagation length in the laser-generated channel of 95 meters. This was accomplished without the use of any solenoidal focusing in this region. It appears that the use of this technique to suppress BBU should permit the extension of high current linear induction accelerators to arbitrarily high energies.

It is a pleasure to acknowledge the help and cooperation of the Advanced Test Accelerator supporting staff.

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Figure Captions

1. The calculated BBU amplitude at the end of ATA vs. peak beam current for maximum strength solenoidal guiding. The width of the shaded band indicates the uncertainty in the cavity parameters ($Z_\perp$) of the BBU mode.
2. Experimental signature of BBU growth down ATA with solenoidal guiding for a 7 kA current pulse. On the left beam current vs. time is plotted at different locations along the beam line showing the decrease of transported current using solenoidal guiding. The current loss occurs primarily in the tail of the pulse where the BBU amplitude is largest. Along the right each oscilloscope trace shows the output voltage from a $\dot{B}_\theta$ loop which responds to the time derivative of the beam's azimuthal magnetic field. The BBU grows with distance down the accelerator until the displacements grow so large that the beam hits the last loop (which is placed near the beam tube wall) shorting it out.
3. Schematic of the ATA beamline showing the injector and accelerator cell block locations. Typical magnetic field and benzene partial pressure axial profiles for laser guiding are shown. The total length of the laser guiding region is 95 meters. The dotted line shows the axial magnetic field profile when solenoidal guiding is employed.
4. Diagnostic waveforms at the end of the accelerator using laser guiding to propagate a 10 kA current pulse. Shown are $\dot{B}_\theta$ loop, current and current-weighted centroid displacement signals. These values correspond to a BBU amplitude of < 0.1 mm., centroid sweeps at all frequencies < 1 mm. and transport of more than 10 kA. The 10 kA current pulse is fully preserved along the entire beam transport line. Visible also is a larger, constant offset of the beam centroid which is due to an offset of the laser with respect to the pipe axis. This offset is easily changed simply by steering the laser beam.

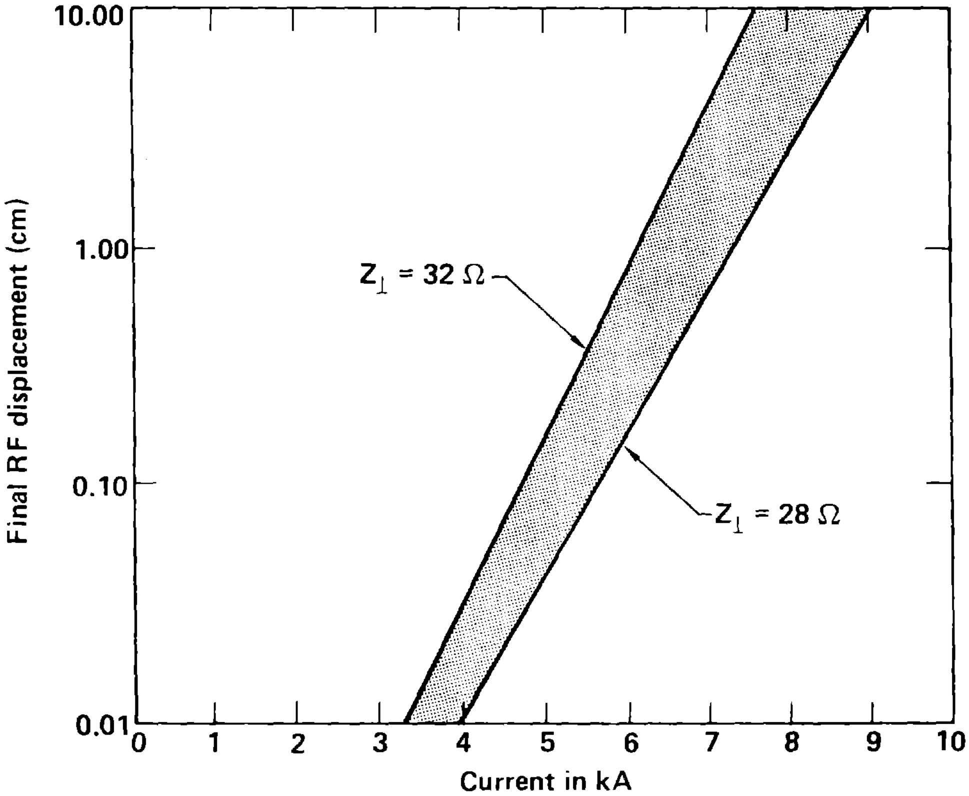
10.00
1.00
0.10
0.01
Final RF displacement (cm)
$Z_\perp$ = 32 Ω
$Z_\perp$ = 28 Ω
0
1
2
3
4
5
6
7
8
9
10
Current in kA

Fig. 1

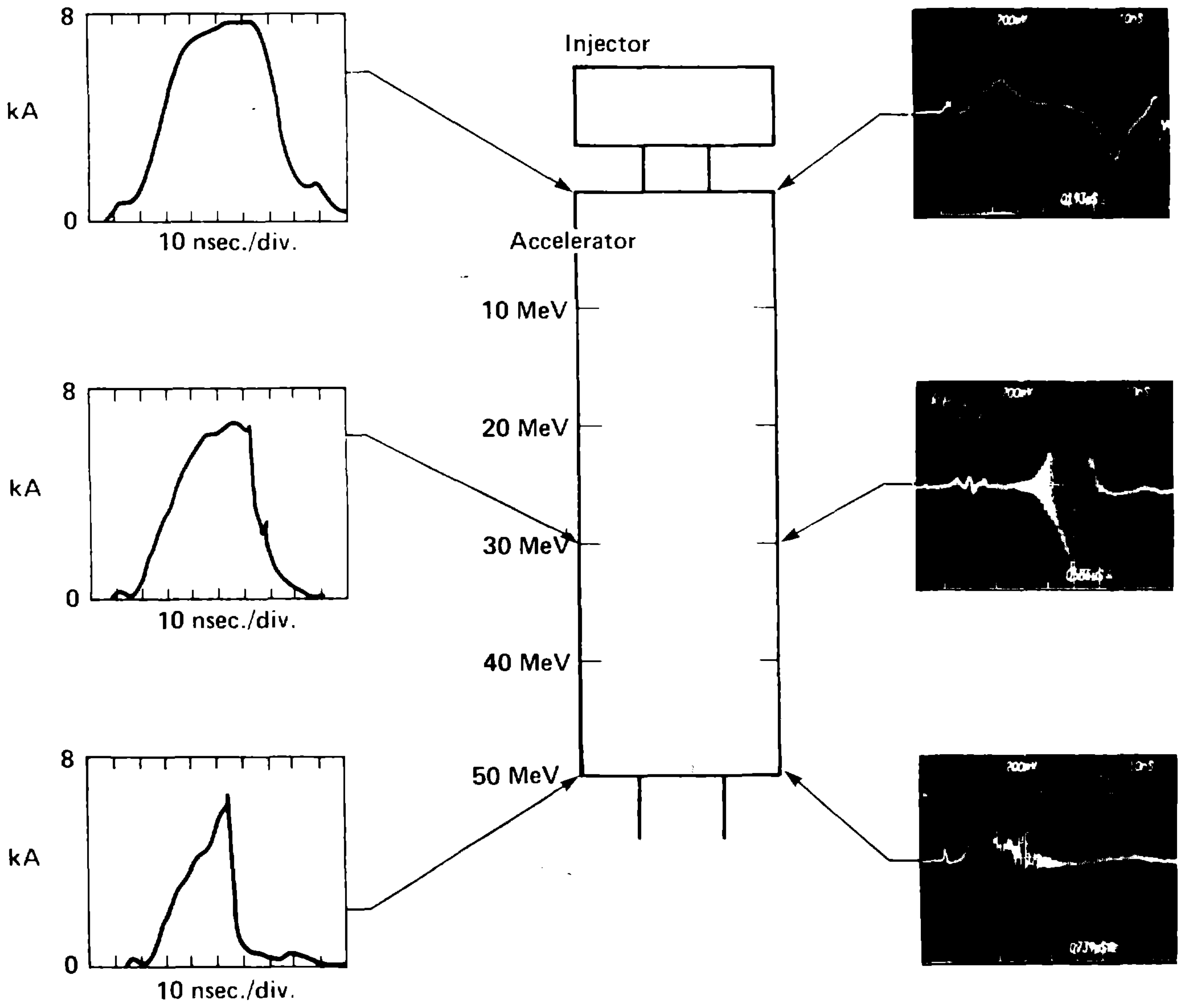
8
kA
0
10 nsec./div.
8
kA
0
10 nsec./div.
8
kA
0
10 nsec./div.
Injector
Accelerator
10 MeV
20 MeV
30 MeV
40 MeV
50 MeV

Fig. 2

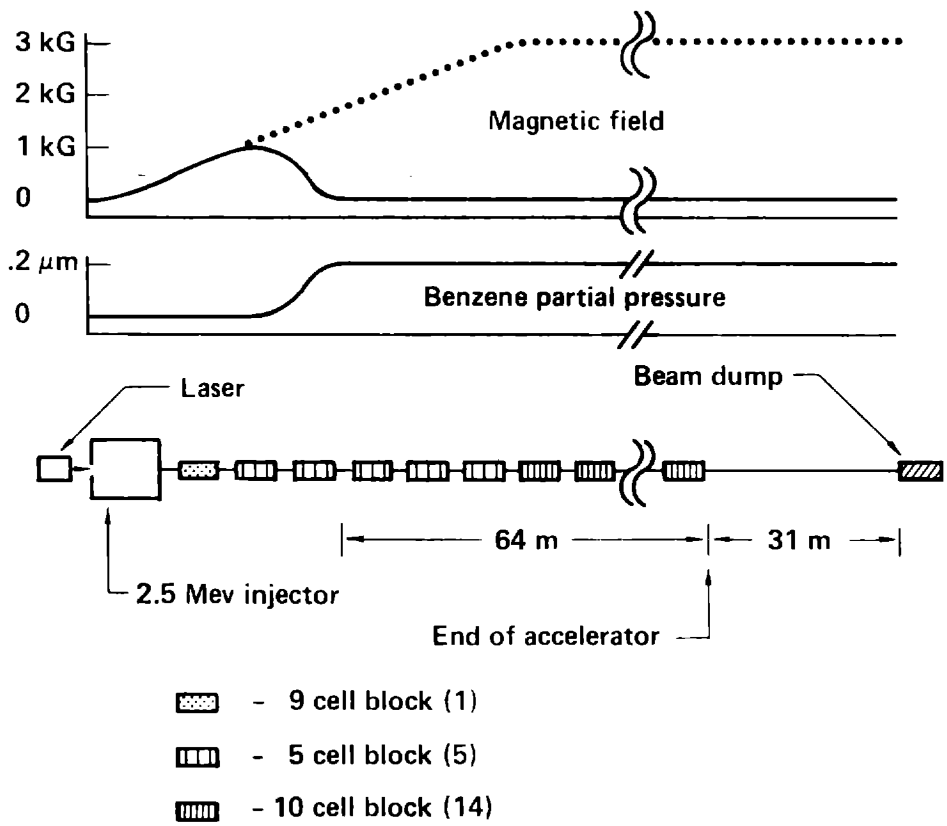
3 kG
2 kG
1 kG
0
Magnetic field
.2 μm
0
Benzene partial pressure
Laser
Beam dump
64 m
31 m
2.5 Mev injector
End of accelerator
- 9 cell block (1)
- 5 cell block (5)
- 10 cell block (14)

Fig. 3

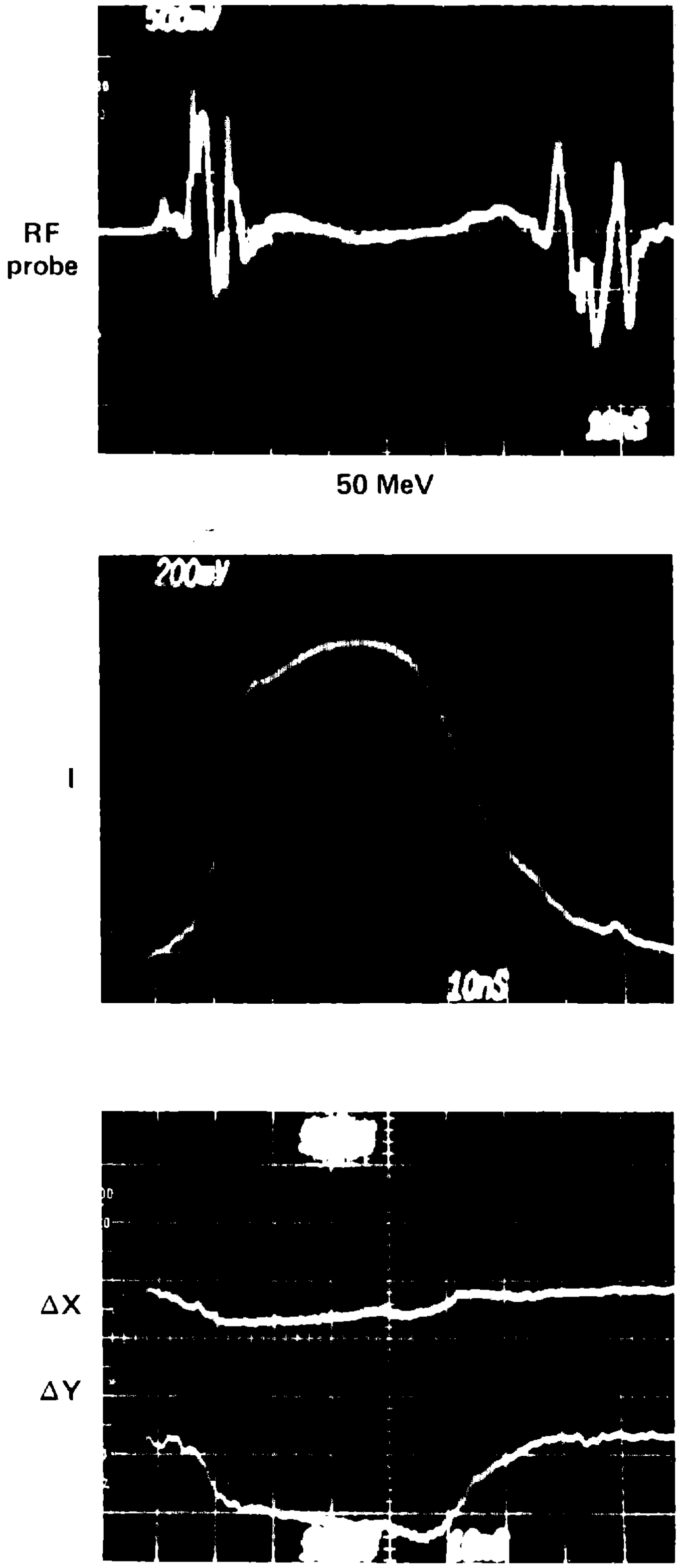

Fig. 4